

Constraints on invisible Higgs decay in MSSM in the light of $h^0 \rightarrow \gamma\gamma$ rates from the LHC

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Abstract

We examine the parameter space of the purely phenomenological minimal supersymmetric standard model (MSSM), without assuming any supersymmetry breaking scheme. We find that a large region of the parameter space can indeed yield the lightest neutral Higgs mass around 125 GeV, as suggested by the recent ATLAS data, and also lead to event rates around, or slightly higher than, the standard model expectation in the two-photon and four-lepton channels. Using a lightest neutralino that is considerably lighter than the Higgs, we find that the ‘invisible’ decay of the Higgs into a pair of neutralinos upto about 10% can be consistent with the current data from the Large Hadron Collider (LHC).

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1 Introduction

The most recent results from the Large Hadron Collider (LHC) keep the hopes for an imminent discovery of the Higgs boson healthily alive. The search results based on an integrated luminosity of 4.9 fb^{-1} are already available. While the mass range approximately between 115 and 127 GeV cannot be ruled out for a standard model (SM) Higgs, the ATLAS collaboration reports hints of an excess around 125 GeV, in both the $\gamma\gamma$ and ZZ^* channels [1, 2, 3, 4, 5]. It may be premature to read too much into this suggested ‘peak’, but it has quite understandably, raised hopes which are reflected in a large number of theoretical papers written since the announcement of the results [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

As of now, the observed signal in, for example, the $\gamma\gamma$ channel is more or less consistent with the standard model expectation, when the Higgs mass is about 125 GeV. At the same time, it is also important to know what the data implies for physics beyond the standard model. The very existence of a low-lying electroweak symmetry breaking sector raises the naturalness and triviality problems, and calls for new physics explanations for the stability of the electroweak scale. The scenario that has drawn maximum attention in this context is supersymmetry (SUSY) [19, 20, 21] which in its minimal phenomenological form (MSSM) is still awaiting a complete probe at the LHC. The fact that the lightest neutral Higgs boson can at most be of mass about 135 GeV makes the currently allowed Higgs mass range a subject of even closer attention from the viewpoint of SUSY. The recent studies [6, 7, 8, 9, 10, 11, 14, 16, 17, 22] consider the implications of the Higgs result in various SUSY scenarios. The present study is another step in this direction, where we have relaxed the requirement of any simplifying SUSY breaking scheme.

The rate in the $\gamma\gamma$ channel, having a small branching ratio, tends to get suppressed when other channels receive any substantial boost. It has been, therefore, argued that the visibility of the Higgs in this channel can be reduced due to enhancement of the $h\bar{b}b$ coupling (where h is the lightest neutral CP-even scalar). This reduction can be compensated, for example, by enhancing the stop mixing angle or by reducing the lighter stau mass [14]. The detailed study of MSSM parameter space that survives the Higgs mass window is presented in [11].

If the lightest neutralino (χ_1^0) is stable, it can serve as a candidate for cold dark matter. At the same time, if its mass is less than half the Higgs mass, the decay $h \rightarrow \chi_1^0 \chi_1^0$ can have a large branching fraction, which in turn may also suppress the $h \rightarrow \gamma\gamma$ branching fraction. We can, therefore, use this information to restrict the MSSM parameter space based on recent hints of Higgs signatures. Though, the importance of the $\chi_1^0 \chi_1^0$ has been pointed out in an earlier study [23], we would like to emphasize its special role when the lightest SUSY Higgs lies in the region 123-127 GeV in the light of the results from the ATLAS collaboration. We would also like to investigate whether it is possible to have SM-like rates in the $\gamma\gamma$ channel even with significant invisible branching fraction. In order to have substantial invisible decay, with the Higgs in the range 123 - 127 GeV, the neutralino has to be less than $\simeq 50 - 60$ GeV. Such values are consistent with the LEP data and all other constraints in the purely phenomenological MSSM.

The most stringent bound on the mass of dark matter particle available till date is from the direct detection experiment XENON100, which imposes bounds on the scattering

cross-section versus WIMP mass in the entire region upto 1 TeV [24, 25]. Recent analysis by CRESST [26] in the low mass region seems to corroborate DAMA/LIBRA [27] and CoGeNT [28] results in favouring light dark matter. Given the stringent bounds in this region from XENON100, there is an obvious tension in the result from the different DM detection experiments. We therefore consider the region with $m_{\chi_1^0} \sim 10\text{-}50$ GeV without imposing any dark matter related constraint. For a study based exclusively on DM constraint, we refer the reader to [29]. Very recently, after the publication of ATLAS data, some study related to SUSY dark matter has been performed in [30, 31].

The questions we propose to answer in this study are as follows. First, do any regions of the MSSM parameter space (with $2m_{\chi_1^0} < m_h$), satisfy the Higgs mass constraint and at the same time reproduce the measured signal strengths in the $\gamma\gamma$ and ZZ^* channels? Second, what regions of MSSM parameter space reproduce SM-like signal strengths in the $\gamma\gamma$ channel. Finally, whether it is still possible to have a significant invisible Higgs decay when the Higgs mass is within 123-127 GeV and $\gamma\gamma$ signal strength is unsuppressed.

Since the phenomenology pertaining to the Higgs sector depends little on the gluino and the first two family sfermion masses, we have assigned large masses to these states, falling back on decoupling as the means of ensuring the suppression of flavour-changing neutral currents. In the same spirit, we have chosen μ to be completely free, and not imposed any condition as such radiative electroweak symmetry breaking to restrict it.

It should be noted that, although our analysis is inspired by dark matter considerations, relying on a light neutralino LSP in the MSSM, it also constrains the parameter space of R-parity violating SUSY as well (where R-parity is defined by $R = (-)^{3B+2S+L}$). While the violation of R-parity can render the lightest neutralino unstable and destroy its candidature for dark matter constituent, a light enough neutralino can still eat heavily into the decay width of the lightest Higgs h and thereby reduce its decay rate in the $\gamma\gamma$ channel. Therefore, if the data on this channel from the LHC continue to maintain the current trend, this channel may successfully probe an R-parity violating SUSY scenario as well.

The strategy adopted for our analysis is outlined in section 2. Section 3 contains the constraints we are able to derive on the MSSM parameter space, with the lightest neutral Higgs capable of decaying into a pair the lightest neutralino. We summarise and conclude in section 4.

2 Strategy for analysis

As has been already stated, we primarily focus on the $\gamma\gamma$ data published recently. The rates in loop-suppressed channels such as $\gamma\gamma$ get substantially affected if the tree-level couplings of the Higgs are altered due to physics beyond the standard model. However, in certain regions of the model parameter spaces, the interplay between the production cross-section and branching ratio can reach an overall rate close to, or, even greater than the SM prediction. Our aim is to first identify such regions in the MSSM parameter space, and then to check if a substantial invisible branching ratio of the Higgs in these regions is still possible.

For calculating the Higgs masses and mixing in the MSSM, we have used the code

FeynHiggs v 2.8.6 [32, 33, 34, 35] which has full two-loop results [36]. First, we scan the MSSM parameter space and select only those points for which the mass of the lightest neutral scalar Higgs (m_h) in the range 123 - 127 GeV. For any given value of $\tan\beta$, the ratio of the vacuum expectation values (vev) of the two Higgs doublets, the neutral pseudoscalar Higgs mass (m_A) is varied appropriately to achieve this, and a scan over the permissible values of m_A is performed in our analysis. It should be kept in mind that m_h in the aforementioned range is crucially dependent on radiative corrections to the potential, largely derived by the top quark and its superpartner. Two-loop corrections to the scalar potential are included for this purpose.

The gluino mass has been fixed at 2 TeV. Squarks of the first two families, too are held fixed at a high mass of 2 TeV, just for simplicity, since they have little bearing on the phenomenology of the Higgs at the LHC. The sleptons are all held fixed at 800 GeV, and the diagonal elements of the stop and sbottom mass matrices, at 1 TeV. The quantities that have been adjusted to obtain the lightest neutral Higgs mass in the desired band are $\tan\beta$ and A_t , the trilinear soft SUSY breaking parameter in the stop sector. The A -parameters in all other sfermion sectors are set to zero.

With the above choice of parameters, we next watch the role of the invisible channel $h \rightarrow \chi_1^0 \chi_1^0$. In particular, we ask the question: is it possible to be consistent with the current LHC data but still be consistent with a substantial invisible branching fraction for h ? For this, first of all, one requires $m_h > 2m_{\chi_1^0}$. Secondly, the composition of χ_1^0 is important in determining the invisible branching ratio. Though μ on the lower side is mostly helpful for this purpose, we vary it over the entire range 100 GeV - 1 TeV, taking care at the same time to confine m_h to the pre-decided range. We hold the M_1 , the U(1) gaugino mass at the representative value of 50 GeV and vary M_2 , the SU(2) gaugino mass across 100 - 500 GeV. We have checked that the conclusions do not differ significantly for values of M_1 in the range 10-50 GeV. Two values of $\tan\beta$, namely, 10 and 40, are used. We use low-scale values of all parameters in our scan. It should be noted that the branching ratio for $h \rightarrow b\bar{b}$ can be as low as 7 - 10% in some regions of the parameter space. This is done most effectively through appropriate values of the stop mixing parameter A_t . Therefore, the effect attempted in reference [14], namely, reducing the $b\bar{b}$ decay width as much as possible, is included in our analysis.

The results presented in the conference note corresponding to the ATLAS analysis [5] for 4.9 fb⁻¹ data give the signal strengths in individual channels where an excess over the background has been observed. Since the production and decay kinematics for SUSY Higgs are not different from a SM Higgs, we assume that the detector efficiency remain the same and therefore the signal in case of a SUSY Higgs can simply be obtained by taking the ratio of the production cross section and the branching ratios in the channel under consideration.

The dominant Higgs production channel is $gg \rightarrow h$. Substantial increase to $b\bar{b} \rightarrow h$ can also be observed in certain regions of parameter space. The next highest contribution to the cross section is in the vector-boson fusion channel which contributes to less than 8% of the total. We therefore use the NLO calculation of $gg \rightarrow h$ and $b\bar{b} \rightarrow h$ available in FeynHiggs to calculate the ratio $R_{\gamma\gamma}$ defined by :

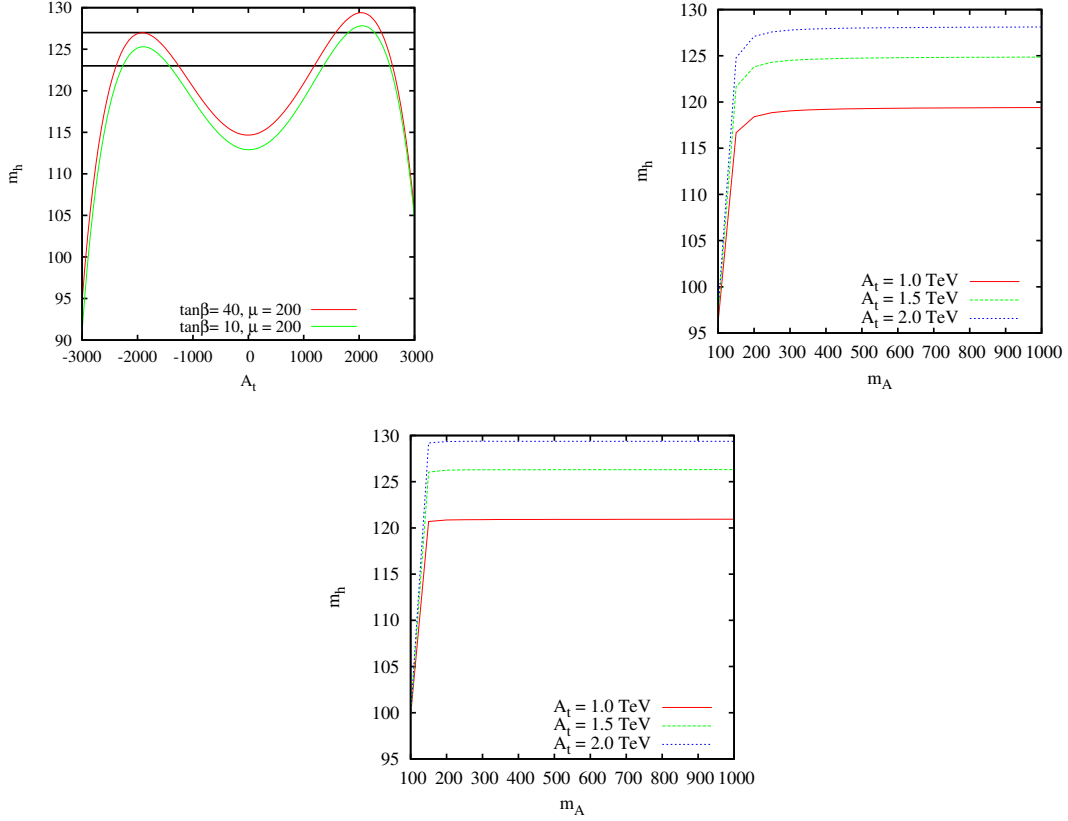


Figure 1: Dependence of Higgs mass m_h on m_A , A_t and $\tan\beta$ for $\mu = 200$ GeV. The first panel (top-left) shows the dependence of m_h on A_t for different values of $\tan\beta$ with. The horizontal band in fig 1(a) corresponds to the ‘favoured’ region seen by ATLAS around $m_h = 125$ GeV. 1(b), (c) are m_A vs m_h curve for various A_t and $\tan\beta = 10$ and 40 respectively.

$$R_{\gamma\gamma} = \frac{[\sigma(pp \rightarrow h) \times BR(h \rightarrow \gamma\gamma)]_{MSSM}}{[\sigma(pp \rightarrow h) \times BR(h \rightarrow \gamma\gamma)]_{SM}} \quad (1)$$

A similar quantity, named R_{ZZ^*} , is defined for Higgs decay into the four-lepton channel via a real and a virtual Z. Since these two are the primary channel in which a signal has been observed, We use these ratios in the next section to determine the favoured MSSM parameter space and the correlation to the invisible Higgs branching ratio.

3 Results

The first objective is to keep m_h , the MSSM lightest neutral Higgs mass, in the neighbourhood of 125 GeV. The Higgs mass is affected strongly by the mass of the CP-odd neutral Higgs m_A and the trilinear stop coupling A_t and the dependence can be seen from Figure 1. The first panel shows the dependence on A_t for different values of $\tan\beta$. Restricting m_h to lie in the window 123-127 GeV restricts the values of A_t to lie within $\pm(1.2 - 2.5)$ TeV.

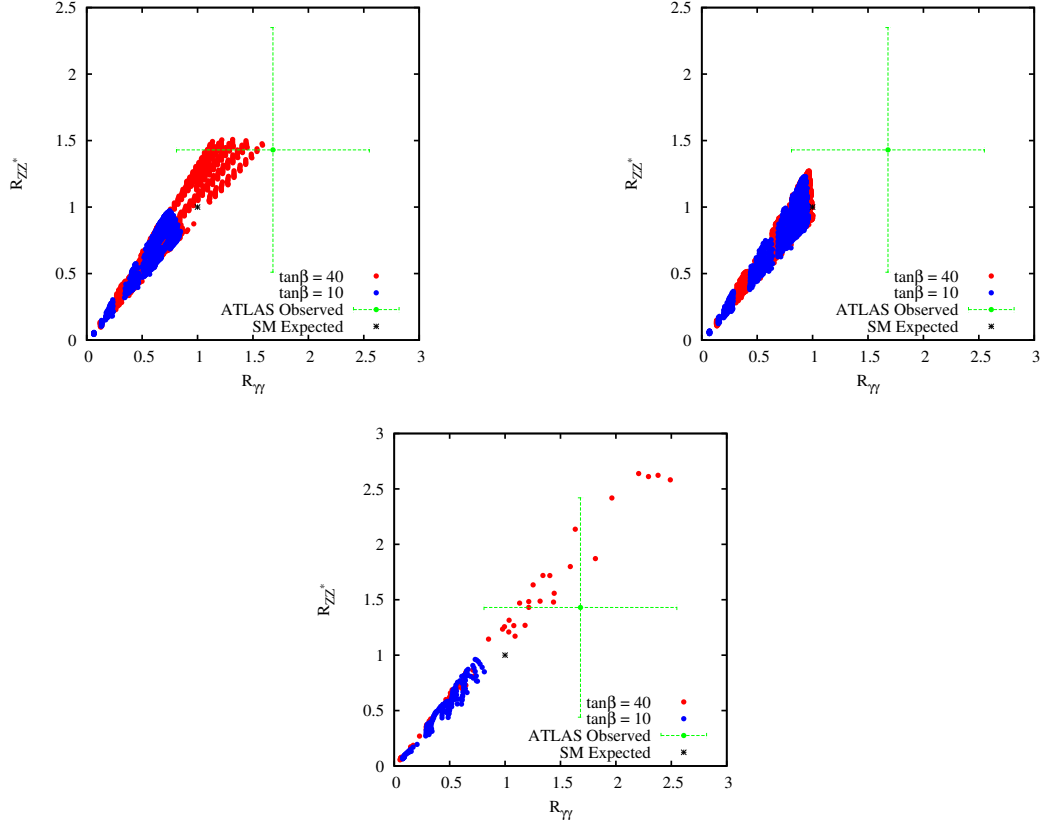


Figure 2: The values of ratios $R_{\gamma\gamma}$ and R_{ZZ^*} for the points in our scan that lie within $123 < m_h < 127$ GeV. We use $M_1 = 50$ GeV for illustration and scan over other parameters (details in the text). The top left panel corresponds to $m_A = 300$ GeV, the top-right to $m_A = 1$ TeV and the bottom panel the the region with $m_A < 300$ GeV. The ATLAS point corresponds to the reported signal strength at the best-fit point with the 1-sigma error bands. The SM point is shown as a black star.

The dependence on m_A can be seen from the second ($\tan \beta = 10$) and third ($\tan \beta = 40$) panels of Figure 1. Increasing $\tan \beta$ reduces the m_A required to reach the maximum Higgs mass value. We also find that the variation of m_A upward of 300 GeV has practically no effect on m_h for the entire allowed range of $\tan \beta$. Although, it does affect the event rates in various channels driven by the production of h . Therefore, for further study, we look into three different regions; first with $m_A = 300$, and 1000 GeV which correspond to the beginning of the region with maximum Higgs mass and the decoupling limit respectively, and the low- m_A region with $m_A < 300$ GeV. We use a value of $\mu = 200$ GeV for illustration in Figure 1, but, the qualitative nature of the curves do not change for higher values of μ .

We now turn our attention to the question of what region is favoured by the current data. Fig. 2 shows the scatter of scanned points in $R_{\gamma\gamma}$ and R_{ZZ^*} . The ATLAS observed point corresponds to the observed signal strength in the $\gamma\gamma$ and ZZ^* channels. The error bars correspond to the 1-sigma errors reported by the experiment. We allow only those points that satisfy the Higgs mass window of 123–127 GeV. The two top panels correspond to $m_A = 300$ GeV and $m_A = 1$ TeV respectively. These two correspond to the region where

the Higgs mass has reached its maximum value for a given A_t . We can clearly see that even though the Higgs mass does not change appreciably in the region (see Fig. 1), the branching ratios change considerably. A lower value of m_A corresponds to larger values of both $R_{\gamma\gamma}$ as well as R_{ZZ^*} . We also see that these two variables are highly correlated and therefore data in the other Higgs decay channels like $b\bar{b}$ and $\tau\bar{\tau}$ will be crucial to realistically rule out any MSSM points. The final panel in Fig. 2 corresponds to the region $m_A < 300$ GeV. This is the only region that is capable of reproducing rates close to the observed ATLAS data point.

In each case, we have used $M_1 = 50$ GeV, and scanned M_2 and μ (the Higgsino mass parameter) over the range 100-500 GeV, and 100-1000 GeV, respectively. Both $\tan\beta = 10$ and $\tan\beta = 40$ have been included in the scans. We find that for $\tan\beta = 10$, it is not possible to achieve values of $R_{\gamma\gamma}$ or R_{ZZ} greater than the SM value of unity irrespective of m_A . Therefore, the currently measured data favours a larger value of $\tan\beta$ in MSSM. It should also be mentioned that the scatter plots in the $R_{\gamma\gamma} - R_{ZZ}$ space are not appreciably different when one reduces the mass of the lightest neutralino to 10 GeV. Thus our conclusions are unaltered even for a relatively light dark matter candidate.

For investigating the invisible Higgs branching ratio, we fix our attention primarily on the $\gamma\gamma$ channel as it currently has much better statistics than the 4ℓ channel. The SM Higgs decay width into two photons is dominated by the W-boson and top loops. In the MSSM case, extra contributions from stop/sbottom and chargino loops also play a crucial role. The last mentioned diagram contributes appreciably only when the lighter chargino is not too heavy (to avoid mass suppression), and at the same time is a nearly equal admixture of gaugino and Higgsino states (to maximize the coupling). This leaves us with a rather small region with $M_2 \simeq \mu < 200$ GeV, where the results are at all sensitive to M_2 . Otherwise, the dependence of $R_{\gamma\gamma}$ on M_2 is hardly noticeable. This is reflected in the left panel of Fig. 3. The second panel, on the other hand, confirms that there is considerable sensitivity of $R_{\gamma\gamma}$ on m_A , due to its effect on the W-loop contribution via the hWW couplings. The dependence on μ also, is significant, as both the panels show. One of the reasons is because of the contributions of the sbottom loop to the $h \rightarrow \gamma\gamma$ decay width. As we have set the parameter A_b to zero, the large values of μ serve as large off-diagonal terms in the sbottom mass matrix and result in one low-mass sbottom state. The sbottom loop contribution to both Higgs production and its decay into two photons goes up in the process. Consequently, one is able to have $R_{\gamma\gamma}$ close to unity and above, by enhancing the value of μ .

The illustrative Fig. 3 uses $A_t = 2.5$ TeV, $M_1 = 50$, $M_2 = 200$ and $\tan\beta = 40$. If the SUSY prediction has to be near about what is predicted by the SM, the region corresponding to $0.8 < R_{\gamma\gamma} < 1.2$ mark a “favoured” band for the purely phenomenological MSSM. Besides this particular case, our scan points to the following broad conclusions. For $m_A = 300$ GeV and $A_t = 1.5$ TeV, we find that $R_{\gamma\gamma} < 0.8$ irrespective of $\tan\beta$. Increasing A_t corresponds to increasing $R_{\gamma\gamma}$ and therefore, we have the appearance of SM-like regions as A_t is increased to 2.5 TeV. We also see from the right panel of Fig. 3 that larger values of m_A increase the value and at the same time decrease the variation in $R_{\gamma\gamma}$ with μ and result in regions with stable $R_{\gamma\gamma}$. Therefore, for $m_A = 1$ TeV, (which also corresponds to approaching the decoupling limit) we have SM-like region even at lower values of $A_t = 1.5$ TeV.

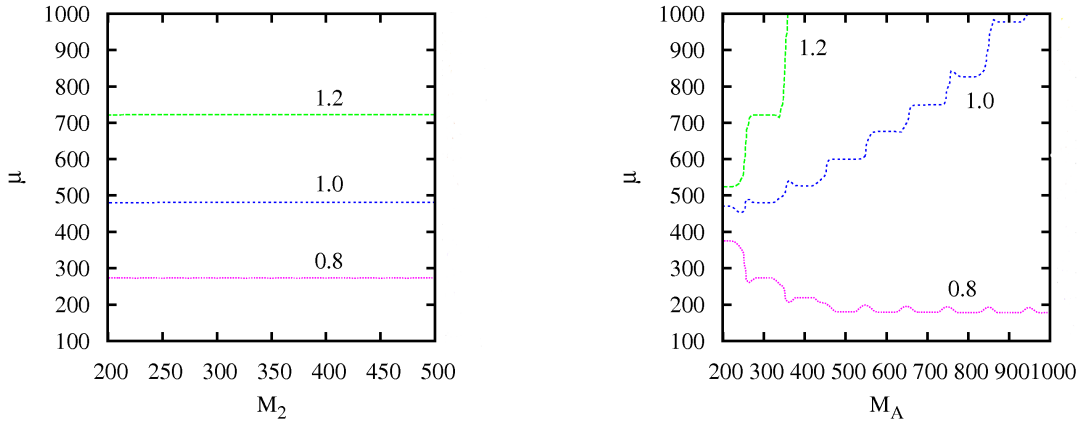


Figure 3: Contours of constant $R_{\gamma\gamma}$ in (left) $M_2 - \mu$ and (right) $m_A - \mu$ space. This plot uses the values $M_1 = 50$ GeV, $\tan\beta = 40$, $A_t = 2.5$ TeV for illustration. The value of $m_A = 300$ GeV in the left panel and the value of $M_2 = 200$ GeV in the right panel is. The pink, blue and green contours correspond to $R_{\gamma\gamma}$ values of 0.8, 1.0 and 1.2 respectively.

Given the distributions of $R_{\gamma\gamma}$ for points in the MSSM parameter space in the allowed Higgs mass range, we now pose the following questions. First, if the ATLAS observed signal strengths are confirmed with more data, is it possible to still have a significant invisible Higgs branching ratio? And, second, if further data is more SM-like, what does that mean for the invisible Higgs decay?

We show the correlation of $R_{\gamma\gamma}$ and $h \rightarrow \chi_1^0 \chi_1^0$ in Fig. 4. In general, we notice a negative correlation between the two quantities. The first panel of Fig. 4 corresponds to the region $m_A < 300$ GeV which we found to be able to reproduce current ATLAS data. However, we find that the region that agrees best with experiment also corresponds to very small values of $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0)$. Therefore, if the current results continue to hold with more data, we do not expect a large invisible Higgs branching fraction. Large invisible fractions of the order of 10% are allowed for $R_{\gamma\gamma}$ in the region 0.6 - 0.8, for all values of m_A as can be seen by comparing the three panels. For $m_A = 1$ TeV (third panel), we see that even $R_{\gamma\gamma}$ upto 0.9 have many points with up to 10% invisible branching fractions.

On the whole, the our analysis suggests that *it is possible to have SUSY contributions to the $\gamma\gamma$ rate at a level comparable to that in the SM, and at the same time allow for an appreciable invisible decay width, if one is faced with a light neutralino dark matter candidate.* However, if the $\gamma\gamma$ rate is larger than the SM rate, any invisible component is likely to be very small and undetectable.

4 Summary and conclusions

We have performed a completely phenomenological analysis, based on MSSM without any model assumptions, of the recent data on Higgs search in the $\gamma\gamma$ and 4ℓ final states, demanding that the lightest neutral Higgs mass be in the range 123 - 127 GeV. The very

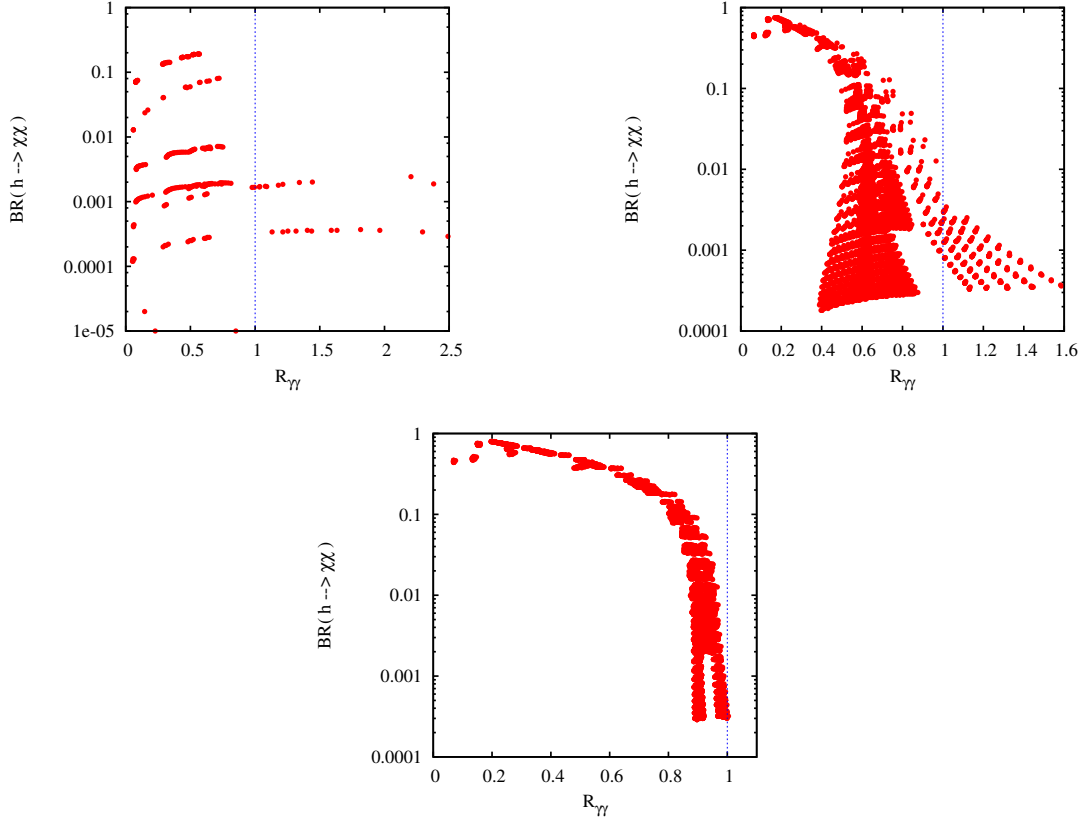


Figure 4: $R_{\gamma\gamma}$ vs $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0)$ plots for (a) $m_A < 300$ GeV, (b) $m_A = 300$ GeV and (c) $m_A = 1$ TeV. The blue line corresponds to SM value of $R_{\gamma\gamma} = 1$.

condition of this mass restriction imposes a considerable constraint on the parameter space when two-loop corrections to the scalar potential are included. Further, we have analysed the parameter space to identify regions where the $\gamma\gamma$ rate is close to what is expected with standard model Higgs of mass 125 GeV. We also compare the $\gamma\gamma$ and 4ℓ rates from the allowed MSSM parameter space to the observed data and to the expected SM rates. Once the Higgs mass is decided, the two quantities that most crucially affect the $\gamma\gamma$ rates are μ , the Higgsino mass parameter, and m_A , the neutral pseudoscalar mass. It is also found that the role of loops driven by the lighter sbottom state can be rather important. In order to see whether there is an irreconcilable tension between a large $\gamma\gamma$ rate and the invisible decay of the Higgs into a pair of LSP, we have deliberately confined ourselves to the case where the lightest neutralino is light. It is found that, inspite of a mild anti-correlation between the two effects, one can still have $R_{\gamma\gamma}$ not too far away from unity and at the same time the invisible Higgs decay branching ratio around 10% in certain regions of the MSSM parameter space.

When a positive signal for the Higgs boson is seen, and the rate in a suppressed channel like the two-photon one is found to be close to what the standard model predicts, it is common to assume that a new physics scenario that entails new decay modes of the Higgs is disfavoured. Our study reveals that it is not so in the phenomenological MSSM, and

that even measurable invisible decay widths of the lightest neutral Higgs can coexist with otherwise SM-like signals. This applies even to the case where R-parity is violated in SUSY and the LSP is liable to decay.

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